"Wire-Cut EDM Machining of Inconel 750: A Comprehensive Analysis of Machinability Characteristics"

SYNOPSIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A DEGREE

OF

DOCTOR OF PHILOSOPHY

IN ENGINEERING

DEPARTMENT OF MECHANICALENGINEERING

SUBMITTED TO

YBN University

Rajaulatu, Namkum, Ranchi-834010, Jharkhand, India

Session 2022-2025

SUPERVISOR

DR. ANJANI KUMAR SINGH

ASSISTANT PROFESSOR
DEPARTMENT OF MECHANICAL ENGINEERING,
SCHOOL OF ENGINEERING AND TECHNOLOGY
YBN UNIVERSITY, RANCHI-834010.

RESEARCH SCHOLAR

AVINASH BHUSAN PAWAN

ENROL. NO. 2202504

DEPT OF MECHANICAL ENGINEERING
SCHOOL OF ENGINEERING AND TECHNOLOGY
YBN UNIVERSITY, RANCHI.

CO-SUPERVISOR

DR. ARVIND KUMAR

ASSISTANT PROFESSOR,
DEPARTMENT OF MECHANICAL ENGINEERING
RTC INSTITUTE OF TECHNOLOGY, RANCHI-835219

CONTENTS

SL. NO.	SUBJECT	PAGE NO.
1	Introduction	3
2	Review of Literature	4-5
3	Objective of the study	5-6
4	Significance of the study	6
5	Study area	6
6	Methodology of research work	6-7
7	Expected outcome	7
8	References	8-9

1. Introduction

Nickel-based superalloys such as Inconel X-750 represent a critical class of materials extensively utilized in aerospace engines, nuclear reactors, gas turbines, and high-temperature structural applications. Their widespread adoption stems from a unique combination of exceptional mechanical strength**,** excellent corrosion and oxidation resistance**,** and superior creep and fatigue performance at elevated temperatures. These attributes are primarily derived from their solid-solution strengthening mechanisms**,** γ' precipitation hardening, and stable microstructural behavior over a broad service temperature range. However, the very properties that make Inconel X-750 indispensable in harsh environments also render it extremely difficult to machine using conventional manufacturing techniques**.** Issues such as rapid tool wear, high cutting forces, poor surface finish, thermal distortion**,** and work-hardening tendencies significantly limit its machinability by turning, milling, or drilling.

To overcome these challenges, Wire-Cut Electric Discharge Machining (WEDM) has emerged as a highly effective non-traditional machining process for such hard-to-cut alloys. WEDM removes material through a series of precisely controlled electrical discharges occurring between a continuously moving wire electrode and the electrically conductive workpiece, both submerged in a deionized water dielectric medium. The absence of mechanical cutting forces, combined with its ability to generate intricate contours, sharp corners, narrow slots, and precise dimensional features**,** makes WEDM particularly advantageous for machining heat-resistant nickel-based superalloys. Moreover, its reliance on thermoelectric erosion rather than mechanical shearing enables the machining of Inconel X-750 with minimal residual stresses and high geometric accuracy**.**

The present study is centered on a comprehensive and systematic evaluation of the WEDM machinability of Inconel X-750. The work investigates the influence of key electrical, mechanical, and flushing-related process parameters—specifically pulse-on time (Ton), pulse-off time (Toff), peak current (Ip), wire feed rate, wire tension**,** and dielectric flushing pressure—on a broad set of performance indicators**.** These include critical productivity metrics such as Material Removal Rate (MRR) and cutting speed**,** as well as quality-related responses like surface roughness (Ra)**,** surface integrity characteristics (including micro-crack formation**,** recast layer thickness**,** and the extent of the heat-affected zone (HAZ)**),** dimensional accuracy**,** geometrical accuracy (flatness, circularity, straightness**),** kerf width**,** and taper error**.**

Divya et al; (2020) By applying rigorous experimental design, advanced statistical modeling, and multi-criteria optimization techniques, this research aims to identify optimal parameter windows that achieve the highest possible machining efficiency while maintaining superior surface finish and minimal thermal damage**.** The development of predictive models will further enable the mapping of complex interactions among process inputs and machining outcomes. The insights generated through this investigation are expected to contribute significantly to the precision manufacturing domain, offering scientifically validated guidelines for machining Inconel X-750 components with enhanced reliability, improved quality, and reduced operational cost. Ultimately, the research addresses pressing industrial

needs in sectors where accuracy, repeatability, and structural integrity of nickel-based alloy components are paramount.

2. Review of Literature

Wire-cut Electrical Discharge Machining (WEDM) is widely recognized for its ability to produce precise and intricate shapes. Owing to its high strength, hardness, and corrosion resistance, the Ni-based superalloy MONEL K-500 is extensively used in aerospace, marine, and automotive applications such as propeller components and pump shafts. WEDM performance depends strongly on input parameters; therefore, proper parameter selection is essential for achieving superior machining quality. In this study, Ton, Toff, gap voltage, wire feed rate, and wire tension were examined using a Taguchi L25 design. Kerf width, MRR, and Ra were optimized through Hybrid Taguchi–Grey Relational Analysis, and SEM was used to evaluate surface morphology (Karthikeyanet al;2022).

Several researchers have examined the machinability of nickel-based superalloys in Wire-Cut Electrical Discharge Machining (WEDM), particularly due to their high strength, thermal stability, and resistance to creep, corrosion, and oxidation at elevated temperatures. One notable study explored the machining behavior of Incoloy-800, focusing on key performance responses such as material removal rate (MRR), surface roughness (SR), and dimensional deviation (DD) under systematically varied WEDM parameters. Using Analysis of Variance (ANOVA), the authors identified the most influential input factors affecting the machining responses and developed statistical models to interpret response trends. The work also incorporated multi-response optimization, employing both the desirability function approach and the teaching–learning-based optimization (TLBO) algorithm to establish an optimal machining parameter combination for simultaneous enhancement of multiple performance indices. Additionally, SEM-based microstructural analysis provided insights into surface morphology and thermal effects induced during machining. This study contributes significantly to understanding the parametric influence and optimization of WEDM for high-temperature superalloys such as Incoloy-800 (Ravi Pratap Singh et al; 2022).

Divya et al; (2020) Wire-cut Electric Discharge Machining (WEDM) has become a widely adopted non-traditional machining process due to its capability to accurately manufacture complex geometries in sectors such as aerospace, defense, transportation, microsystems, and agricultural machinery. Its suitability for machining hard, conductive, and difficult-to-cut materials, including metal-matrix composites, ceramic composites, and superalloys, has been well documented. Superalloys, developed primarily for aerospace and power-generation applications, offer exceptional mechanical strength, creep resistance at elevated temperatures, and excellent corrosion and oxidation resistance. Numerous studies have focused on optimizing WEDM input parameters using techniques such as the Taguchi method, ANOVA, Grey Relational Analysis (GRA), Artificial Neural Networks (ANN), and Principal Component Analysis (PCA). These methods have been applied to evaluate the influence of parameters such as pulse-on time, pulse-off time, servo voltage, peak current, and kerf width on key responses like Material Removal Rate (MRR) and Surface Roughness (SR). Results consistently highlight Taguchi-based experimental design and ANOVA as effective tools for achieving higher MRR and improved surface quality.

K. Satyanarayana et al; (2021) Research on superalloys has gained significant attention due to the need to establish optimal machining conditions for these difficult-to-cut materials. Their exceptional performance—characterized by high strength, hardness, and stability at elevated temperatures—has led to extensive use in aerospace, marine, and nuclear industries. Among these materials, Inconel 600 poses considerable challenges to conventional machining, making non-traditional processes such as Wire-cut Electric Discharge Machining (WEDM) more suitable. One study investigated the WEDM machining of Inconel 600 using uncoated zinc wire, employing a Taguchi L9 design with varying pulse-on time (Ton), pulse-off time (Toff), and peak current while keeping voltage and dielectric flow constant. The optimization targeted lower surface roughness and higher material removal rate (MRR). Regression modelling yielded high predictive accuracy (R^2 = 91.84% for surface roughness and 92.61% for MRR). ANOVA results indicated that Ton significantly affects surface roughness, whereas current predominantly influences MRR.

3. Objective of the Study

i. To systematically evaluate the influence of the primary WEDM process parameters—pulse-on time (Ton), pulse-off time (Toff), peak current (Ip), wire feed rate, wire tension, and dielectric flushing pressure—on the overall machinability performance of Inconel X-750. This includes detailed assessment of:

- Productivity metrics, specifically Material Removal Rate (MRR) and cutting speed.
- Surface quality characteristics, including surface roughness (Ra) and surface integrity, with emphasis on micro-crack formation, recast layer thickness, and the extent of the heat-affected zone (HAZ).
- Dimensional and geometrical accuracy, measured through flatness, circularity, and straightness.
- Cut-feature accuracy indicators, such as kerf width and taper error.

ii. To develop robust predictive models using advanced statistical and computational techniques such as Response Surface Methodology (RSM) and Artificial Neural Networks (ANN), enabling accurate prediction of key machining outputs. Further, to use Analysis of Variance (ANOVA) to identify the most significant process parameters and their interactions.

iii. To optimize the WEDM process parameters through suitable multi-objective optimization approaches—including Desirability Function Analysis, Grey Relational Analysis (GRA), and TOPSIS—with the aim of simultaneously maximizing productivity (MRR and cutting speed) and minimizing thermal and surface defects (Ra, recast layer, micro-cracks, and HAZ).

iv. To conduct detailed characterization of surface integrity using state-of-the-art analytical tools such as Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), microhardness profiling, metallography, and X-ray Diffraction (XRD). This objective focuses

on establishing clear correlations between WEDM parameters, microstructural transformations, and near-surface mechanical/thermal responses.

v. To validate the optimized machining parameters by performing confirmation experiments and applying them to machining industrial-relevant geometries such as thin walls, intricate radii, precision slots, and complex contours on Inconel X-750 workpieces. This step ensures the practical applicability, reliability, and robustness of the developed models and optimization strategy.

4. Significance of the Study

- Provides a comprehensive machinability map of Inconel X-750 under WEDM for precision, high-reliability parts.
- Bridges the gap between high productivity and surface integrity requirements—critical for aerospace, nuclear, and energy sectors.
- Contributes to academic literature via integrated analysis of electrical + mechanical + flushing parameters over multiple performance metrics, especially recast/HAZ behavior in precipitation-hardened nickel alloys.

5. Study Area

- Material: Inconel X-750 (nickel-chromium alloy, precipitation-hardened by Ti/Al additions), standard plate/blank samples (e.g., 10–20 mm thickness), solution treated and precipitation hardened per supplier specification.
- Machine: Industrial Wire EDM with CNC control, deionized water dielectric, programmable Ton, Toff, Ip, servo gap control, wire feed and wire tension adjustment.
- Electrode (wire): Brass / zinc-coated brass (e.g., 0.25 mm diameter); optional trials with molybdenum for comparison.
- Environment: Controlled dielectric conductivity (via resin), temperature-stable lab with calibrated metrology.

6. Methodology of Research Work

Experimental Design

- Factors (Inputs):
  - Ton (µs),
  - Ip (A),
  - Wire feed (mm/min),

- Wire tension (N),
- Dielectric flushing pressure/flow (L/min).

- Ranges (indicative, to be finalized by pilot runs):

  - Ton: 0.5–12 μs
  - Ip: 2–12 A
  - Wire feed: 3–12 m/min (machine-dependent)
  - Wire tension: 5–20 N
  - Flushing: 4–12 L/min; nozzle stand-off: 0.5–1.5 mm

- Design of Experiments:
  - Taguchi orthogonal array (e.g., L27 for six factors × 3 levels).
  - Replicates to estimate experimental error; randomization to avoid bias.

Measurement & Characterization

- Productivity
  - MRR
  - Cutting Speed
- Surface & Integrity
  - Surface Roughness (Ra, Rz)
  - Surface Integrity:
    - SEM for micro-crack density and morphology,
    - EDS for elemental changes (recast oxides, carbides),
    - Metallography with etching to measure recast layer thickness and HAZ; image analysis software for thickness mapping,
    - Microhardness traverses from surface to bulk to quantify hardening gradients,
    - XRD residual stress for near-surface stress states; optional EBSD for microstructural changes.
- Dimensional & Geometrical Accuracy
  - CMM or toolmaker's microscope for dimensions, flatness, circularity, straightness per ISO standards.
  - Kerf width: Optical microscopy across multiple sections; statistical mean ± SD.
  - Taper error

Data Analysis.

7. Expected Outcome

- Quantified influence of Ton, Toff, Ip, wire feed, tension, and dielectric flushing on all key machinability characteristics of Inconel X-750.
- Predictive models (equations/ML) for MRR, cutting speed, Ra, Rz, recast thickness, HAZ, accuracy, kerf, and taper error, with validated confidence intervals.

8. References

1. Karthikeyan, A. G., Kalaiselvan, K., & Muralidharan, N. (2022). CNC wire-cut EDM input variables analysis on Ni -based superalloy (MONEL K-500). Materials and Manufacturing Processes, 37(9), 1035–1044. https://doi.org/10.1080/10426914.2021.2001522
2. Ravi Pratap Singh, Ravinder Kataria, Mustufa Haider Abidi, Sudhir Ranjan, Ashutosh Kumar Gupta & Abdulrahman Al-Ahmari (2022) Surface Morphology And Machinability Aspects In Wire-EDM of Incoloy-800 Superalloy: An Experimental Evaluation And Microstructure Analysis Surface Review and Letters Vol. 29, No. 08, 2250105, https://doi.org/10.1142/S0218625X22501050
3. Divya Marelli,Singh S.K, Sateesh Nagari , Ram Subbiah ,(2020) Optimisation of machining parameters of wire-cut EDM on super alloy materials–A review, Materials Today Proceedings, Volume 26, Part 2, 2020, Pages 1021-1027.
4. K. Satyanarayana, M. Mounika, Kumkuma Raj Kiran (2021) Experimental studies and optimization of WEDM process in machining of Inconel 600 using zinc wire, Materials Today Proceedings, Volume 44, Part 1, Pages 2431-2434.
5. Agarwal V, KhanguraSS, Garg RK (2015) Parametric Modeling and optimization of wire electrical discharge machining of Inconel 718 using response surface methodology. Int J AdvManuf Techno 79:31-47 [6] [7] [8] [9] [10] [11]
6. V Muthukumar,NRamesh,RVenkataswamy:Mathematical Modeling for Radial overcut on Electrical Discharge Machining of incoloy800 by Response Surface Methodology,Procedia Material science 6(2014)1674-1682.
7. Syed Asghar Husain Ruzvi,SanjayAgarwal: An Investigation on Surface Integrity in EDM process with a copper tungsten electrode,Procedia CIRP 42(2016)612-617.
8. M SreenivasaRao and N Venkaiah: Experimental investigations on surface integrity issues of Inconel-690 during wire-cut electricaldischargemachiningprocess, JournalofEngineeringManufactureIMeche (2016).
9. Anil kumar,SachinMaheswari,Chitrasharma and Naveen beri:Analysis of Machining Characteristics in Additive mixed Electrical Discharge Machining of Nickel based super alloy Inconel 718,Materials and Manufacturing processes,26:1011-1018,2011.

10. Naveen beri,Sachinmaheswari,Chitra Sharma and anil Kumar: “Surface Quality Modification using powder metallurgy processed CuW during electrical discharge machining of Inconel 718electrode”,International conference of on advances in manufacturing and material engineering,AMME 2014,Procedia Material Science 5 (2014) 2629-2634.
11. M Manohar,Tselvaraj,D Siva Kumar and Kosh M George Experimental study to assess the effect of bottom profiles while machining Inconel 718 through EDM process,Procedia Material Science 6 (2014)92-104.
12. Mathew, A.T.: Innovative Design, Analysis and Development Practices in Aerospace and Automotive Engineering (I-DAD 2018) (2019)
13. Xavior, M.A., Ashwath, P., Ali, H., Moideen, A., Banu, P., Illanthendral, Sancylal, S.: Effect of recast layer thickness on the mechanical characteristics of INCONEL 718 machined by spark EDM process. Mater. Today: Proc. 5(2), 8249–8255 (2018)
14 Mandal, A., Dixit, A.R., Das, A.K., Mandal, N.: Modeling and optimization of machining nimonic C-263 superalloy using multicut strategy in WEDM. Mater. Manuf. Process. 31(7), 860–868 (2016)
15. Singh, R.P., Singhal, S.: Rotary ultrasonic machining: a review. Mater. Manuf. Process. 31, 1795–1824 (2016)
16. Singh, R.P., Singhal, S.: Investigation of machining characteristics in rotary ultrasonic machining of alumina ceramic. Mater. Manuf. Process. 32, 309–326 (2017)